



# TFAWS Aerothermal Paper Session



## Optical Diagnostic Imaging of Multi-Rocket Plume-Induced Base Flow Environments

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# Launch Vehicle Failures Due to Base Heating



- Launch vehicles with multi-rocket engine base region
- Highly complex base flows due to changing multi-plume interactions and freestream flow
  - Difficulty in numerically predicting such environments
  - No analytical solution of this flow regime
- Base thermal protection system (TPS) protects avionics, wiring, engine gimbal actuators, turbomachinery, etc.
- Led to the failures of many launch vehicles due to vehicle control loss by not adequately predicting base environments

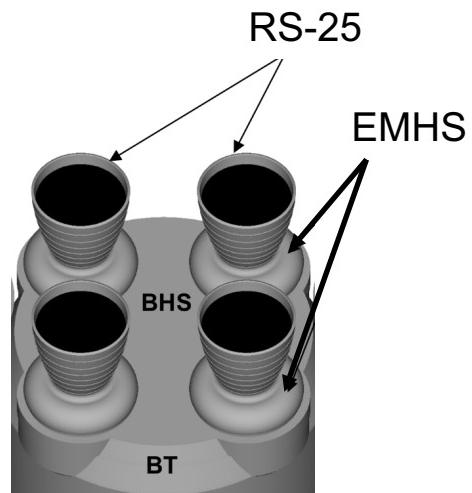
Rocket	Date	Outcome	Cause
JUPITER AM-1A	3/1/57	Failure	Base heating - Control Loss
ATLAS SM-65 A	6/11/57	Failure	Base heating - Control Loss
ATLAS SM-65 A	9/25/57	Failure	Base heating - Control Loss
THOR 114	1/1/58	Failure	Base heating - Control Loss
POLARIS A-1	12/30/58	Failure	Base heating - Control Loss
POLARIS A-1	1/9/59	Failure	Base heating - Control Loss
SATURN I	10/21/61	Concern	Base heating - Base Flow
SATURN IB	2/26/66	Concern	Base heating - Base Flow
SATURN V	11/6/67	Concern	Base heating - Base Flow
N-1 (SOVIET)	2/1/72	Failure	Base Flow - Roll Control
MAXUS (GERMAN)	5/1/91	Failure	Base heating - Control Loss
PROSPECTOR	6/19/91	Failure	Base heating - Control Loss



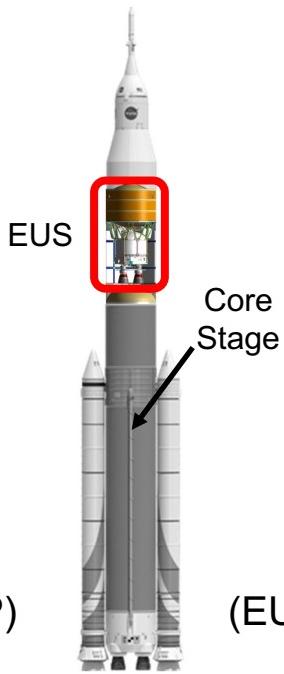
# Short-Duration Base Heating Tests



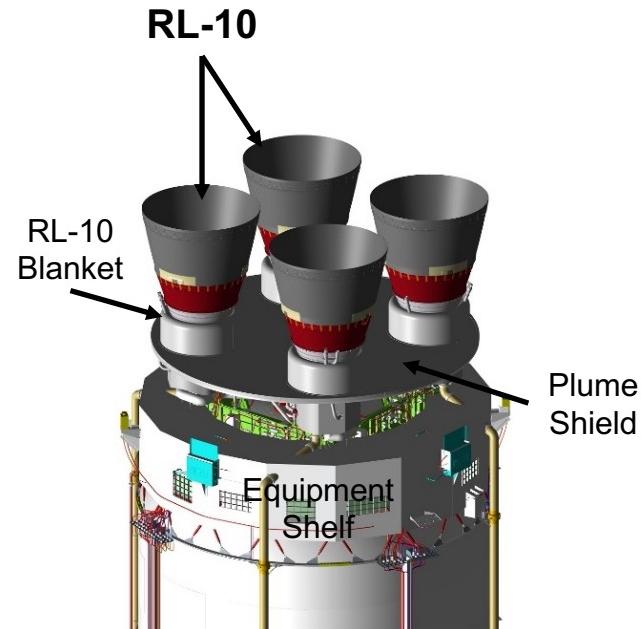
- Both test programs were conducted at CUBRC Large Energy National Shock Tunnel I (LENS I) facility in 2016 to investigate launch vehicle base and plume flows
- FY16 TIP – 2% model; EUS – 3.23% model
- Rekindled NASA ground test techniques from the 1970s<sup>1</sup>
- Simulate >150,000 ft altitude conditions



Space Launch System (SLS) Core Stage Base  
(FY16 Technology Innovation Program – FY16 TIP)



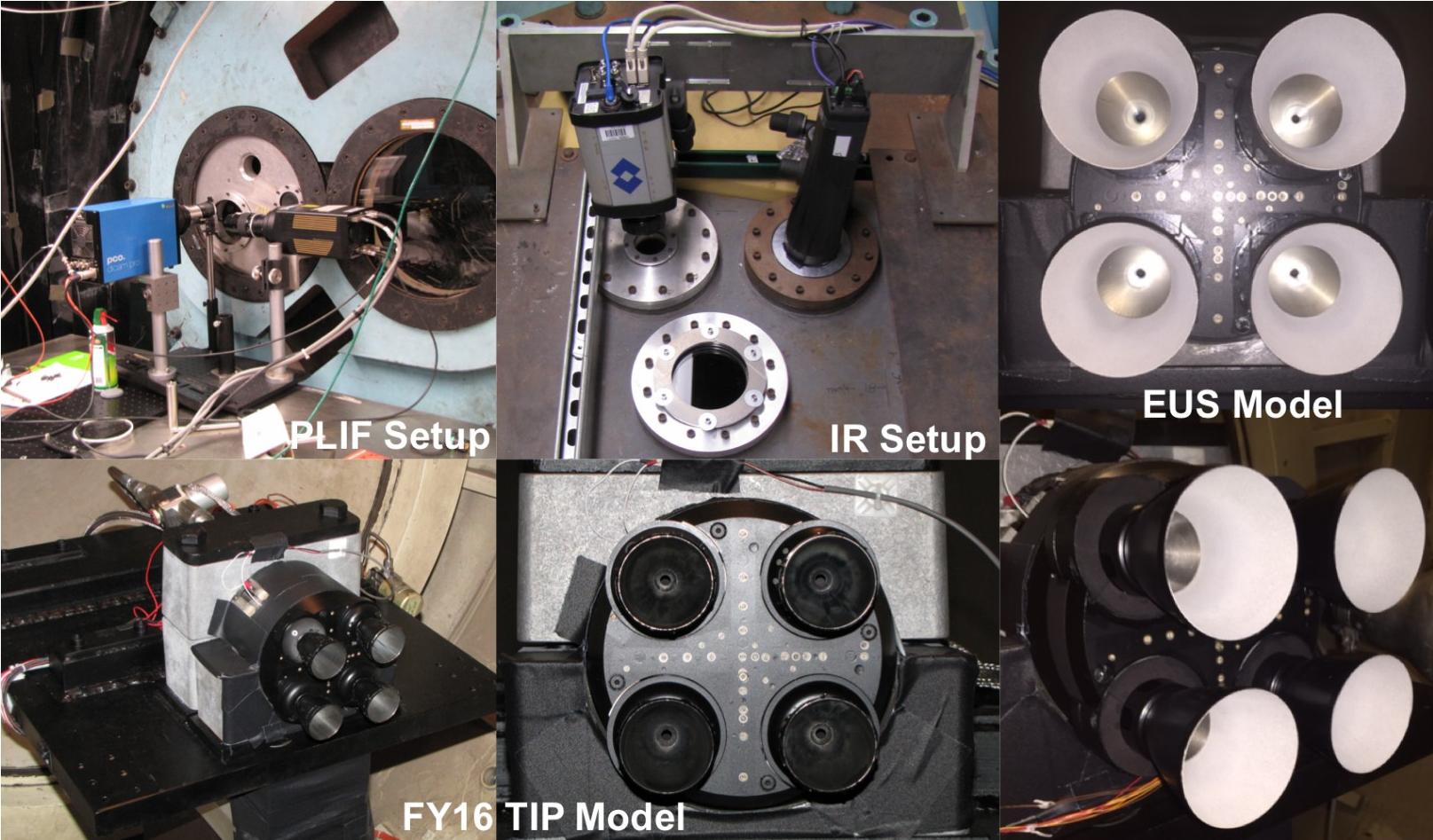
Exploration Upper Stage Base  
(EUS Base Heating Test Program - EUS)



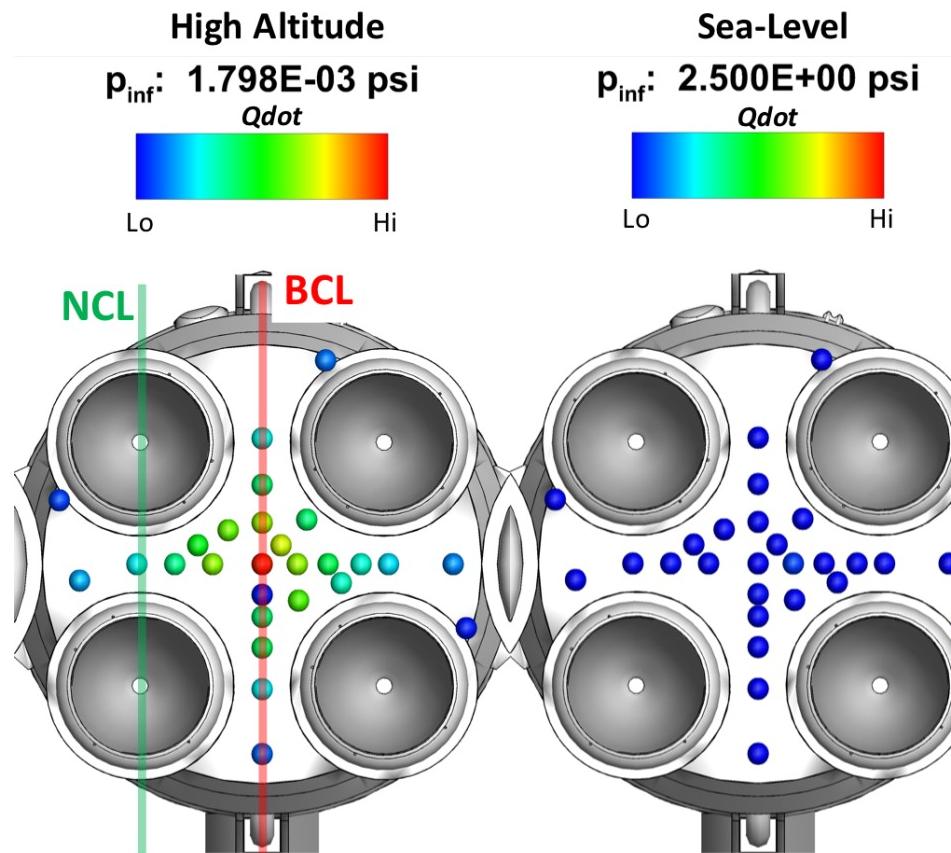
# Short-Duration Test Propulsion Models



- NASA Marshall & CUBRC developed propulsion models for the SLS and EUS base heating test programs in a shock tunnel<sup>2</sup>
- Hydroxyl radical - planar laser induced fluorescence (OH-PLIF) and infrared (IR) imaging were used for the **first time** to visualize both base flow and plume environments



- TIP main objective was to determine the feasibility to visualize and characterize base and plume environments for launch vehicle ascent flight using non-intrusive diagnostics in shock tunnel facility
- NCL = nozzle centerline, BCL = base centerline
- GO<sub>2</sub>-GH<sub>2</sub> rocket engine performance (a,b,e,f)
- Base environments for sea-level and high altitude (~170,000 feet) conditions (c,d,g,h)
  - Thin-film heat transfer gauges
  - Piezo-resistive pressure sensors

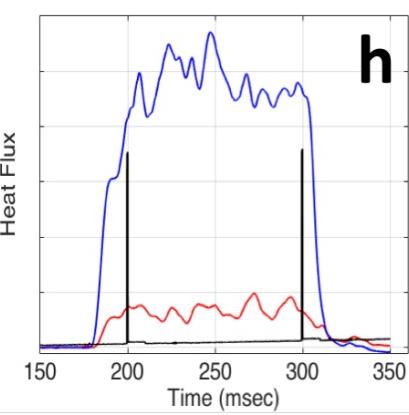
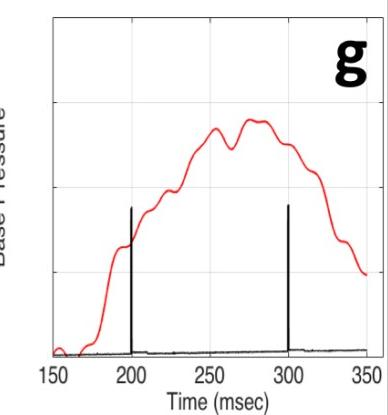
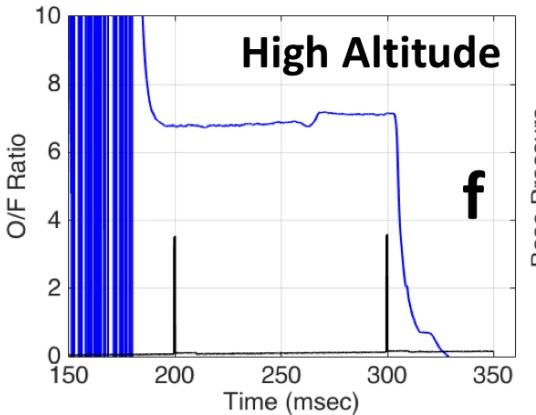
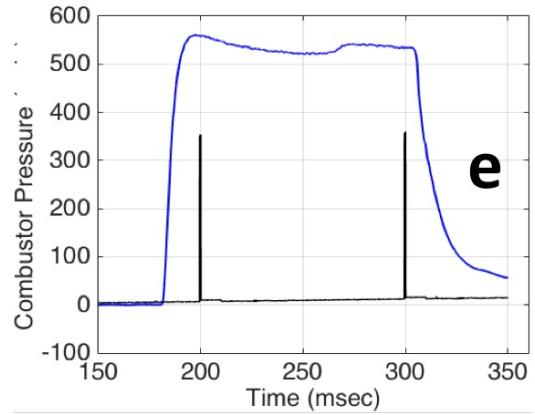
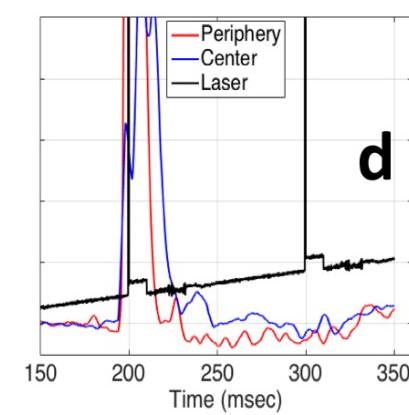
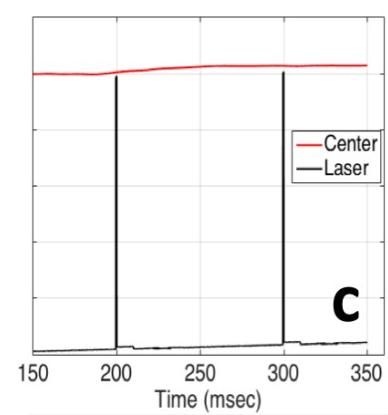
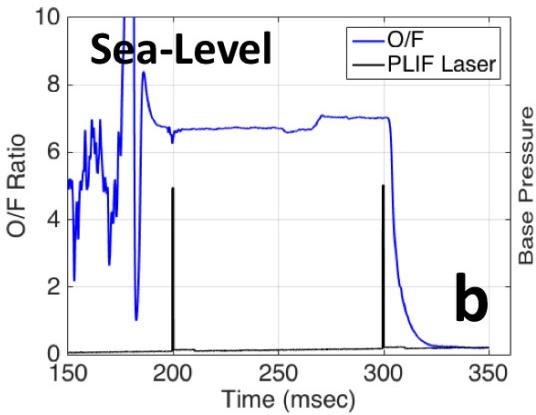
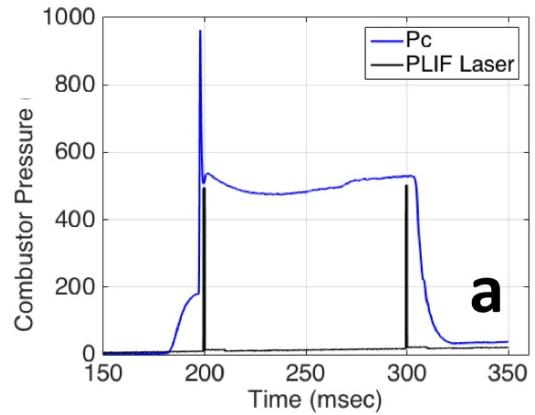
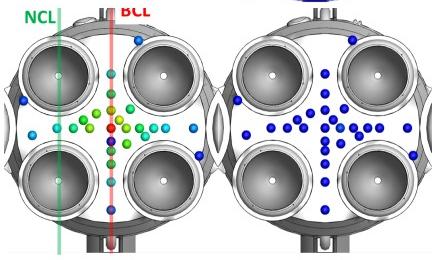




# FY16 TIP Base Environments

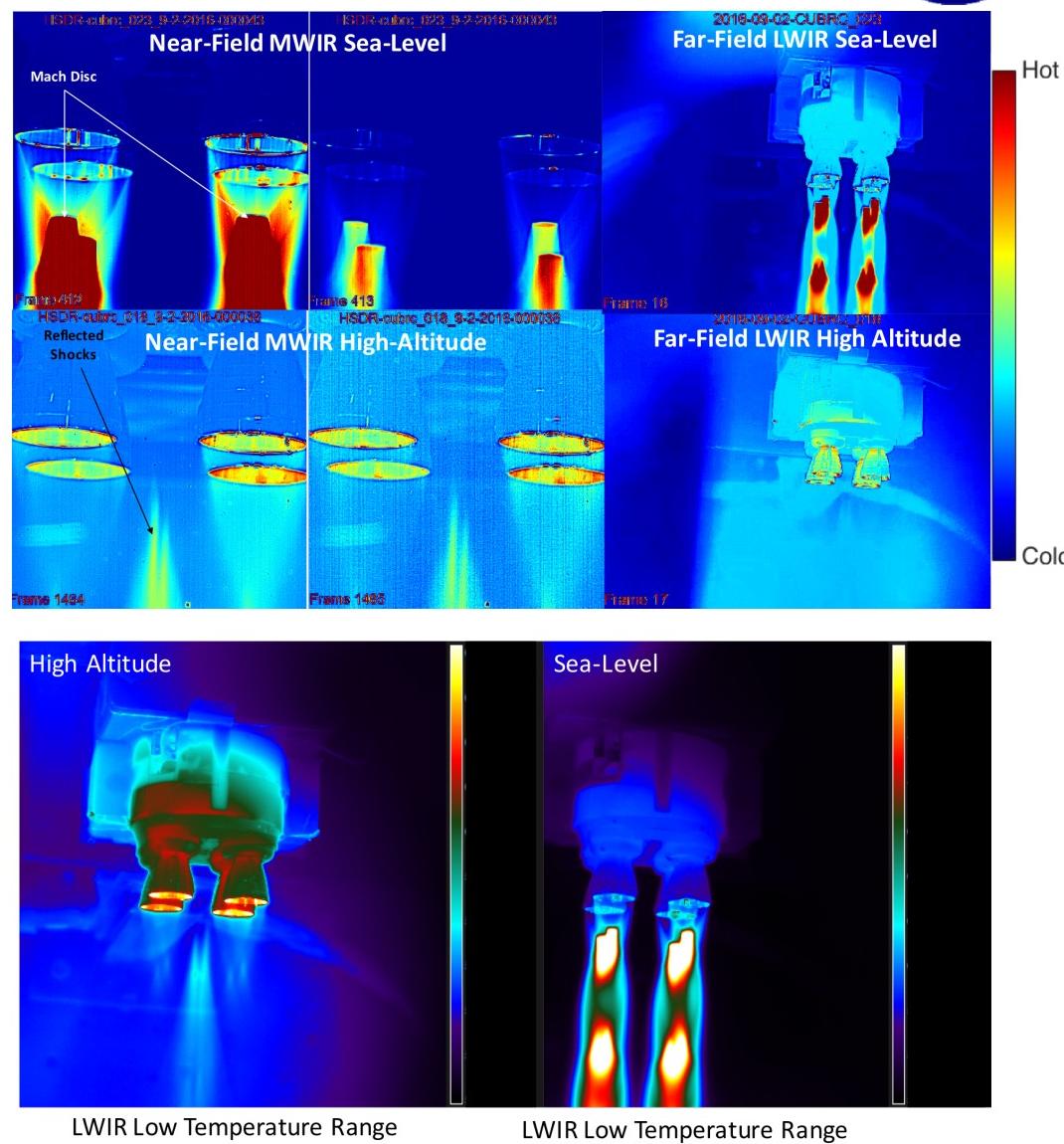


- GO<sub>2</sub>-GH<sub>2</sub> rocket engine performance (a,b,e,f)
- Base environments for sea-level and high altitude (~170,000 feet) conditions (c,d,g,h)
  - Thin-film heat transfer gauges
  - Piezo-resistive pressure sensors

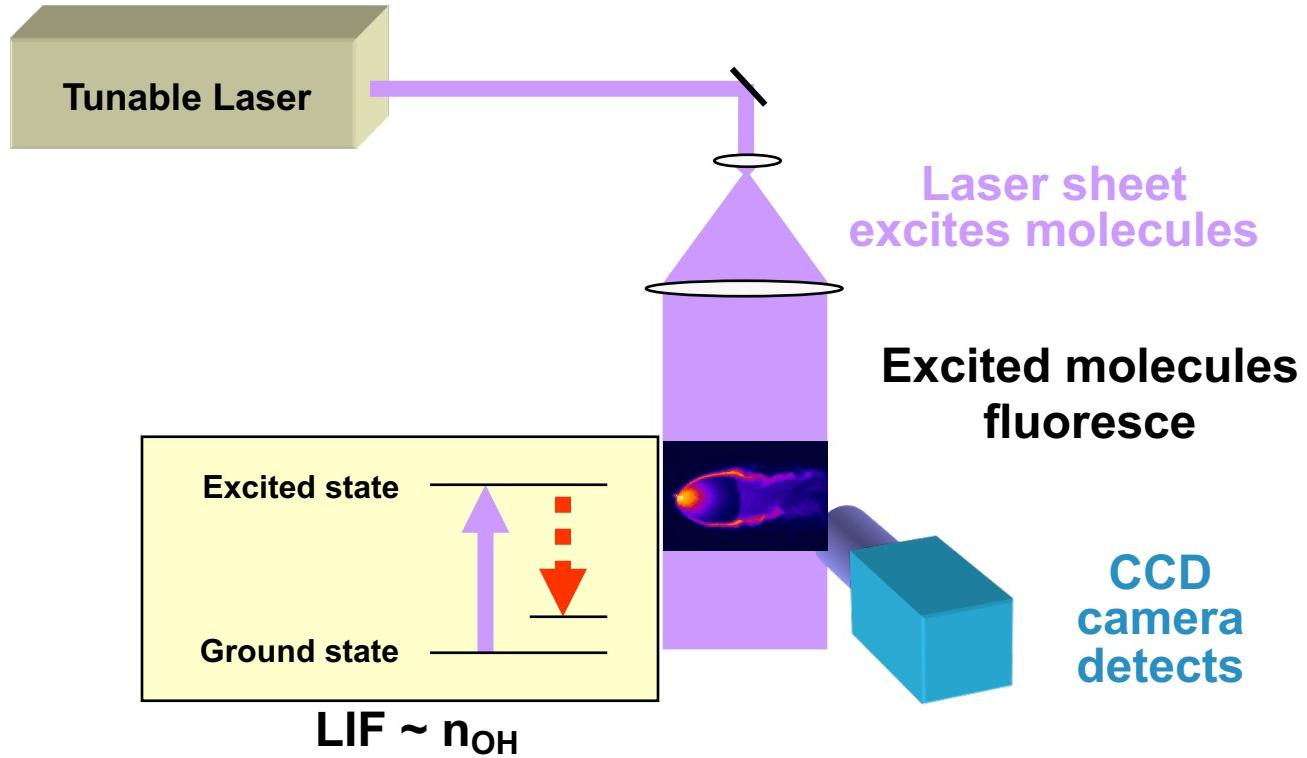


# FY16 TIP IR Imaging

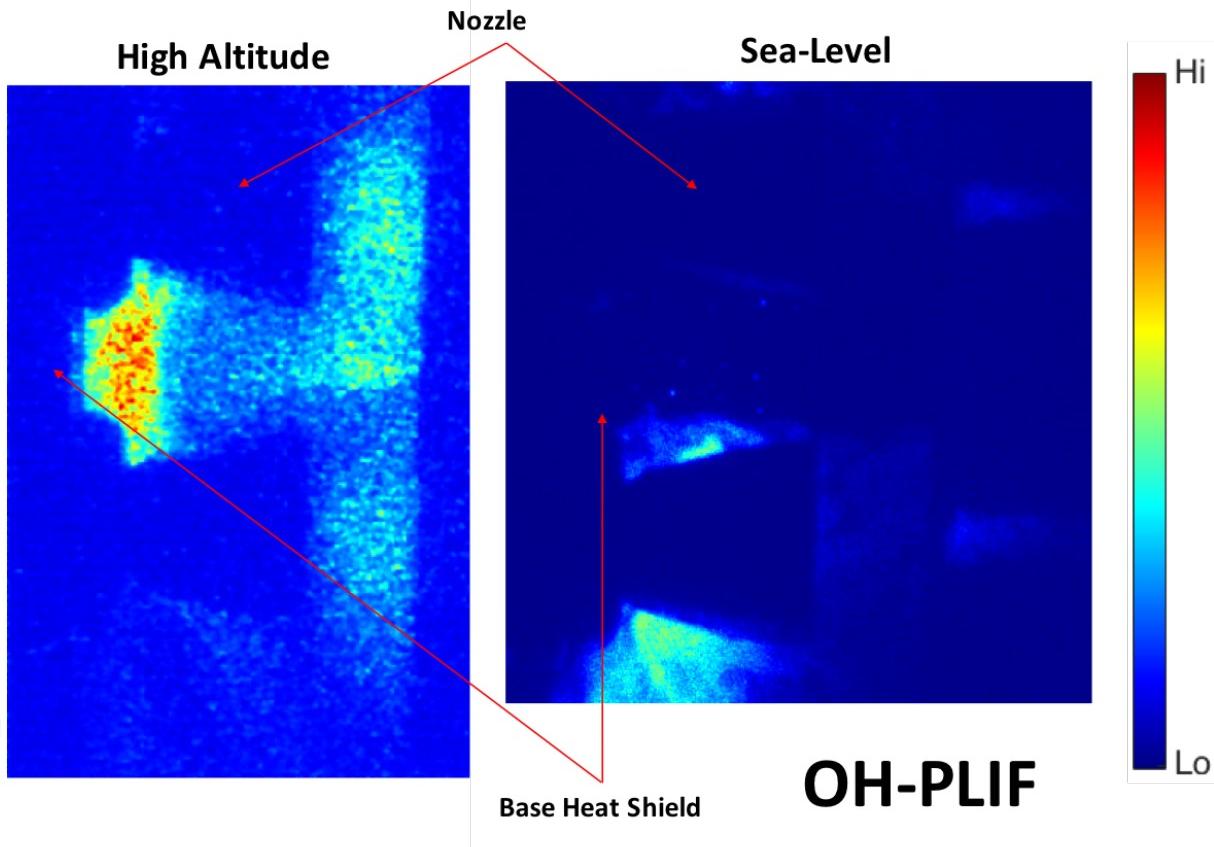
- Long-wave IR ( $7.5\mu\text{m} – 14\mu\text{m}$ ) camera
  - Focused on the far-field
  - Calibrated for surface wall temperature characterization
- Mid-wave IR ( $3\mu\text{m} – 5\mu\text{m}$ ) camera
  - Focused on the near-field
  - Ideal to visualize base flows
  - Low and medium temperature sensitive to distinguish flow features
- Different plume flow structures between high altitude and sea-level conditions



# Planar Laser-Induced Fluorescence (PLIF)<sup>3-4</sup>

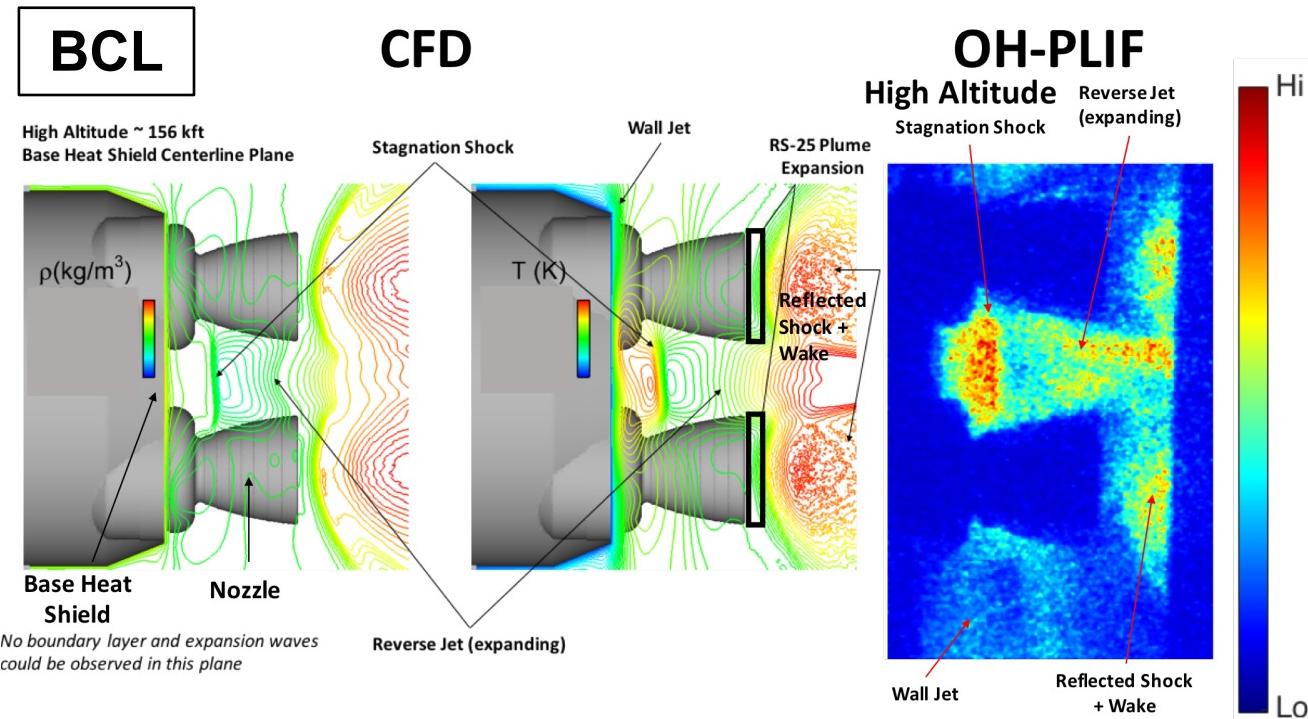


- Hydroxyl radical (OH) used as naturally occurring fluorescent tracer
  - Combustion intermediate species
- 10 ns Nd:YAG dye laser sheet at 20 mJ/pulse excites OH at 285.53 nm for flow visualization
  - Flow freezing images
- Two intensified CCD cameras with OH LIF transmitting filters were positioned normal to the laser sheet
- Different base flow structures observed between high altitude and sea-level conditions
  - Base flow structures not observed with CO<sub>2</sub>– MWIR or schlieren imaging



- Base flow structures were successfully visualized using OH-PLIF
  - Shows OH emission intensity
  - Assuming constant mole fraction, frozen flow, extract **qualitative** gas temperature map
- Observe good qualitative agreement between test data and computational results
- Complex base flow structures
  - Stagnation shock
  - Reverse jet
  - Reflected shocks
  - Wall jet

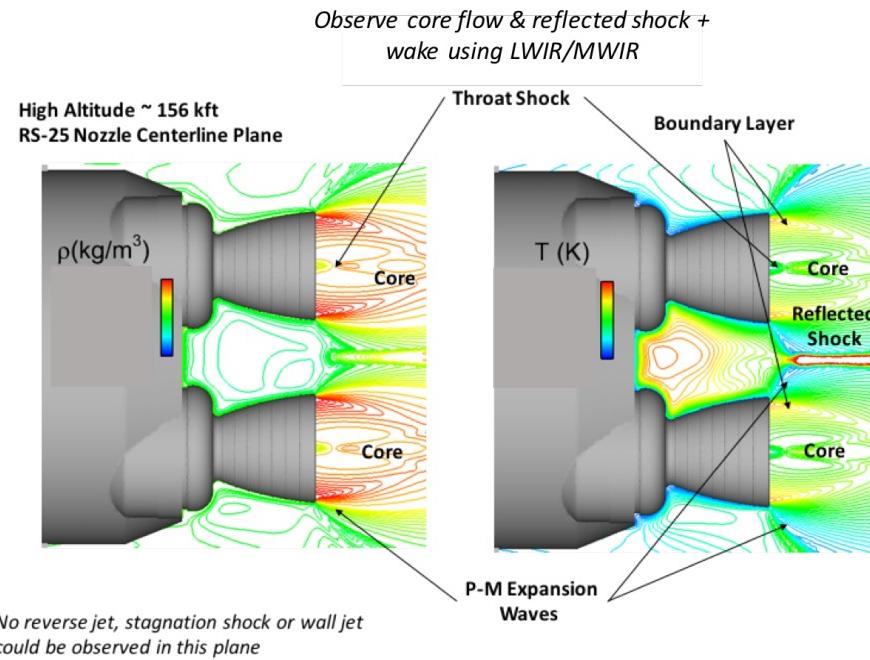
- Need to assess stagnation shock RS-25 nozzle impingement region
- Shock impingement can augment heating by a factor of ~10
- Interaction first discovered by PLIF imaging



*CFD solutions provided by F. Canabal (MSFC-EV33)*

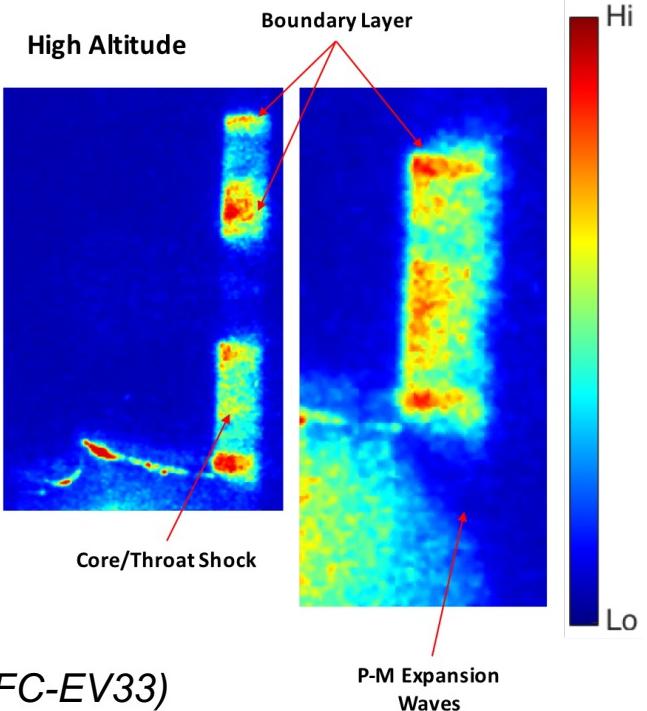
- Near-field plume flow structures were successfully visualized using OH-PLIF
- Observe good qualitative agreement between test data and computational results
- Complex plume flow structures
  - Hot boundary layer
  - Throat shock (cooler core flow)
  - P-M expansion waves

## CFD



## OH-PLIF

## NCL

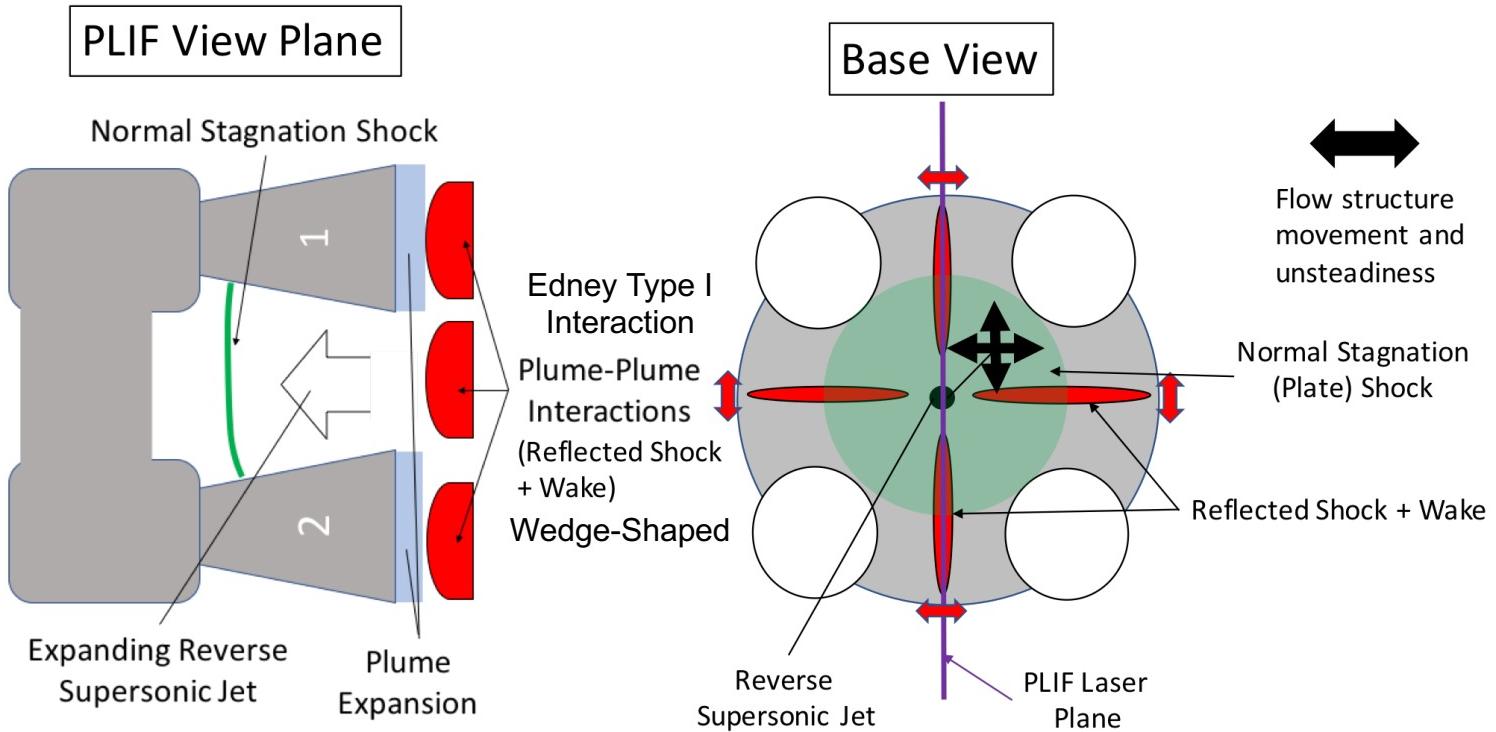


CFD solutions provided by F. Canabal (MSFC-EV33)

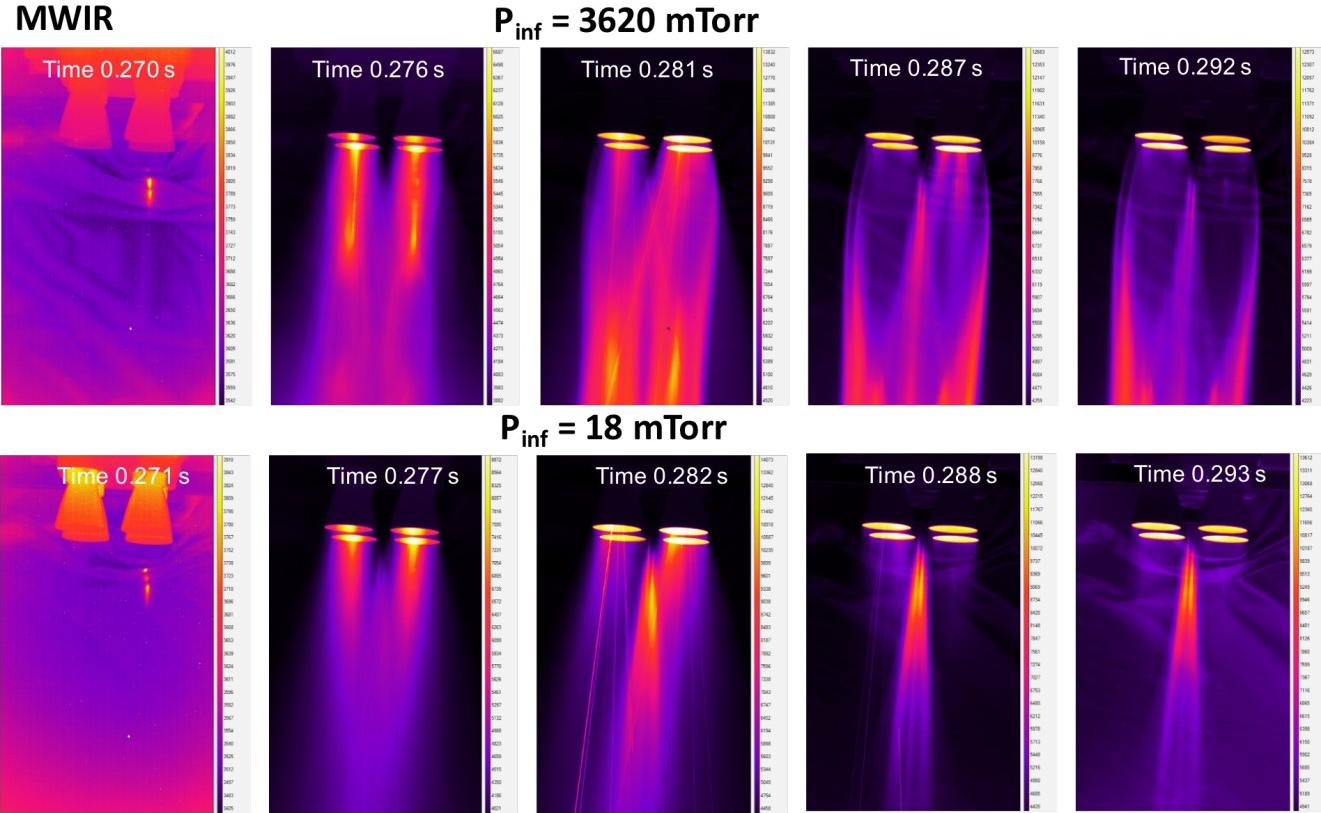
# High-Altitude 4-Engine Base Flow Model



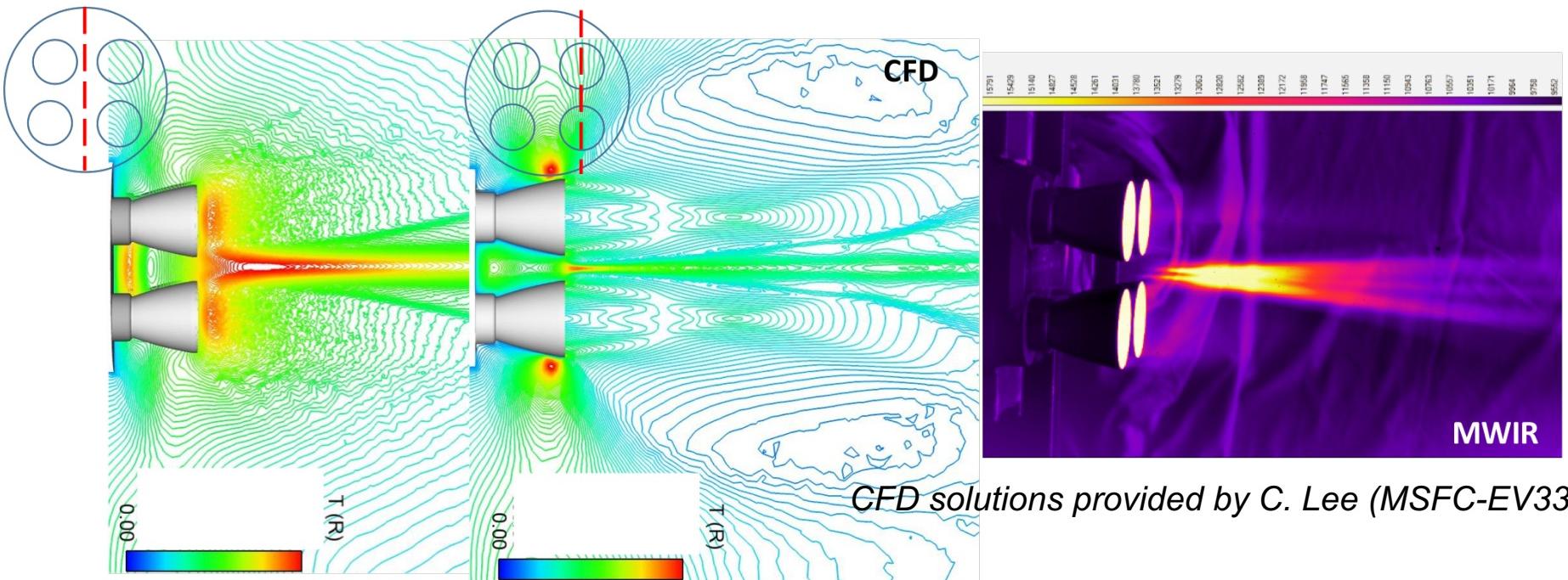
- Based on FY16 TIP imaging data analysis, 4-engine base flow model developed and builds upon existing base flow theories<sup>5</sup>
- Many unsteady flow structures lead to changes in the imaging data



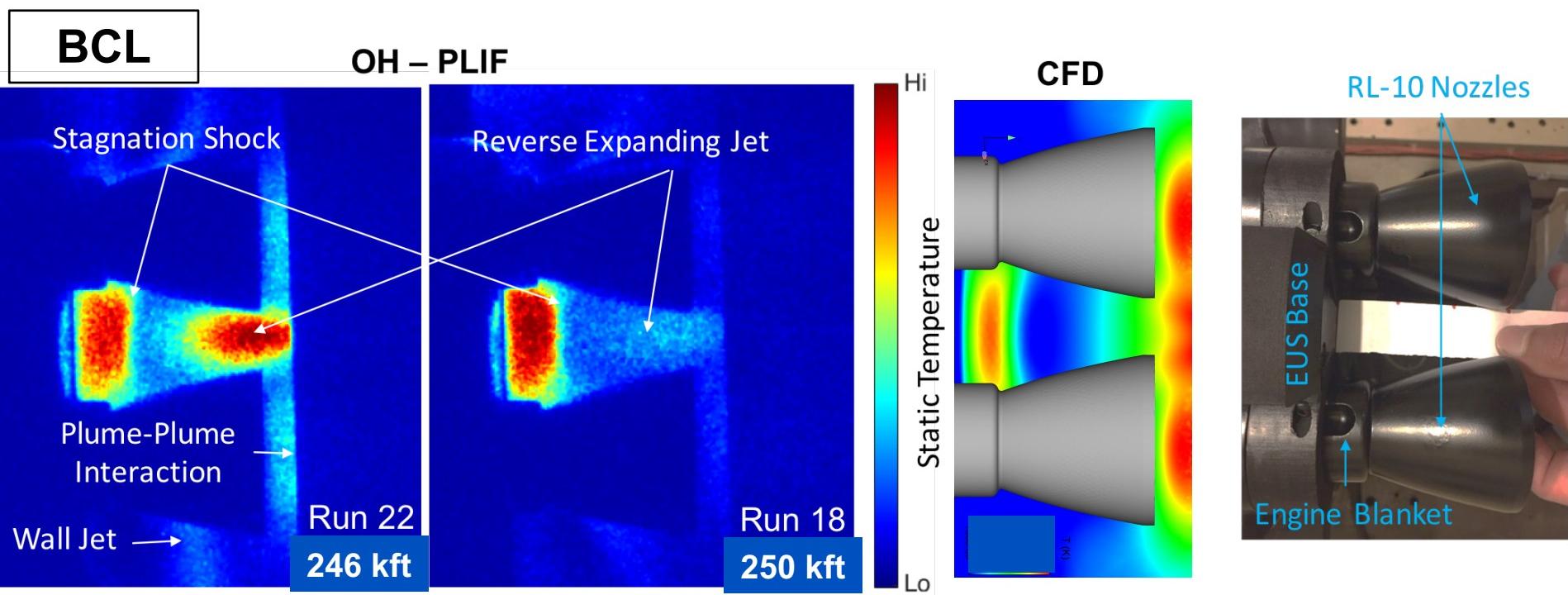
- EUS test main objective was to predict base convective heating environments and visualize base/plume flows using ground test data
- MWIR imaging of sub-scale EUS propulsion model start-up
- Observe differences in plume structure between sea-level and high-altitude conditions (~240,000 ft) within steady-state regime
- Need optically thick hot gas to be observed with IR



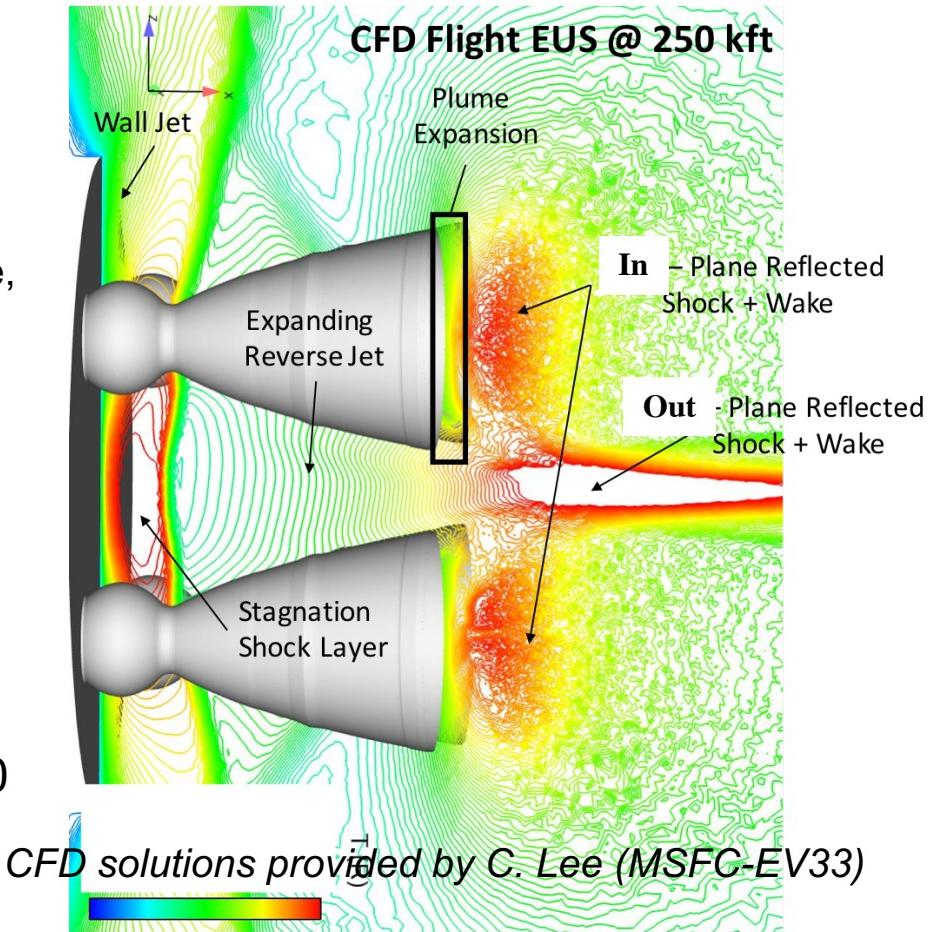
- IR imaging is spatially averaged data taken between 100 Hz and 180 Hz
- Good qualitative agreement observed between IR data and computational solutions
- Major feature observed is the 4-lobed reflected shocks and their wake



- Good qualitative agreement observed between PLIF data & computational solutions
- All major base flow structures observed
  - Similar to SLS core-stage base flow (TIP) and confirms 4-engine base flow model
- Similar flow structures and qualitative trends observed between ground test data and CFD



- Observe similar flow structures between ground test PLIF imaging, test model CFD and flight CFD solutions
  - Similar concave stagnation shock structure, stand-off distance and shock diameter
  - Similar in-plane reflected shock contours
  - Similar expanding reverse jet
- Suggests sub-scale ground test simulates appropriate flow physics to flight
  - Provides further confidence in plume-induced flight environments based on ground test
- Need to assess stagnation shock - RL10 nozzle impingement



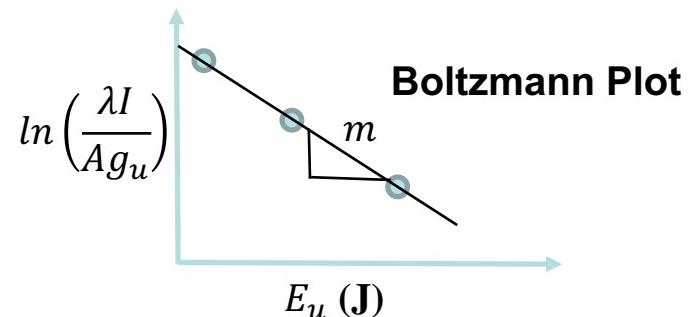
- $\ln\left(\frac{\lambda I}{Ag_u}\right) = \frac{-E_u}{kT} + C_1$  where  $\lambda, A, g_u, E_u, k, C_1, I$

and  $T$  are the targeted wavelength, transition probability (Einstein coefficient), multiplicity of the upper state, excited state energy, Boltzmann constant, linear equation constant, measured line intensity and excitation temperature

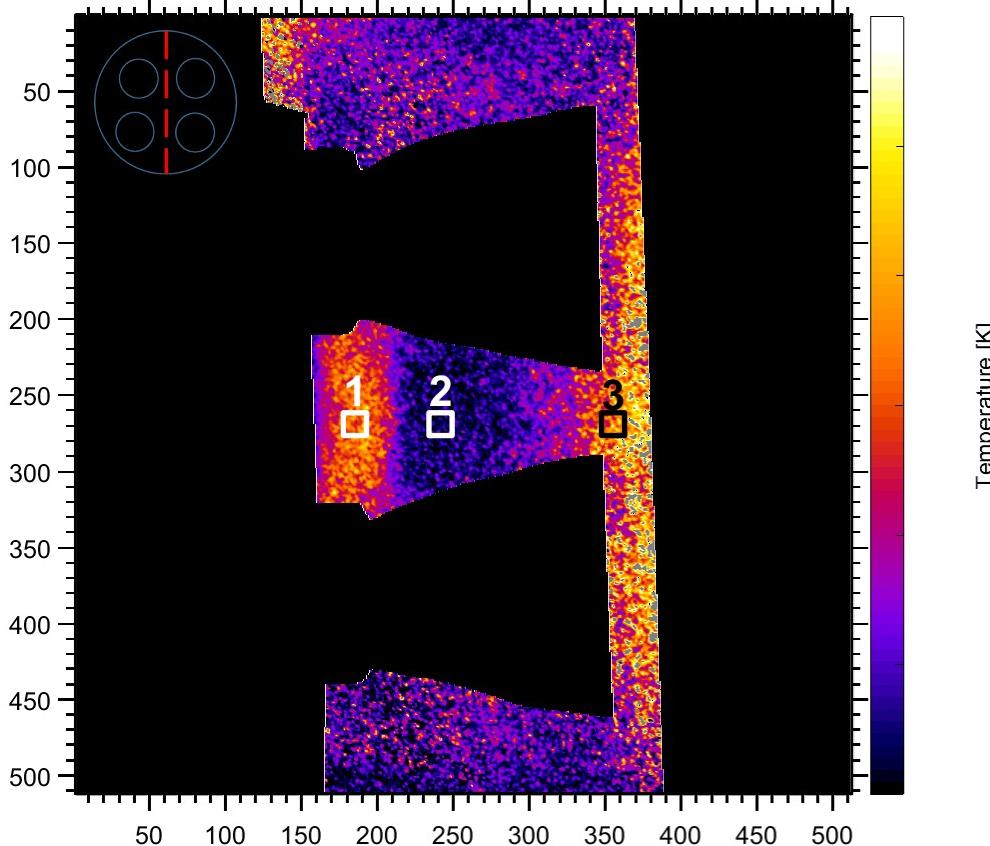
- $S = \lambda I; C = Ag_u$
- $m = \frac{-1}{kT}$  (slope of  $\ln\left(\frac{S}{C}\right)$  vs.  $E_u$  plot)
- $A, g_u, E_u, k$  are determined from handbooks of spectroscopic constants, chemistry and physics
- $\lambda, I$  are obtained from the test program
- From the slope of the Boltzmann plot, temperature of the targeted gas can be estimated

5 test runs were used at three  $\lambda$  targets

Run #	name	J	$\lambda$ (nm)
39	Low J	Q2(6)	283.380
22	mid J	Q1(8)	283.553
23	High J 1	Q2(12)	285.545
24	High J 2	Q2(12)	285.545
8	mid J	Q1(8)	283.553



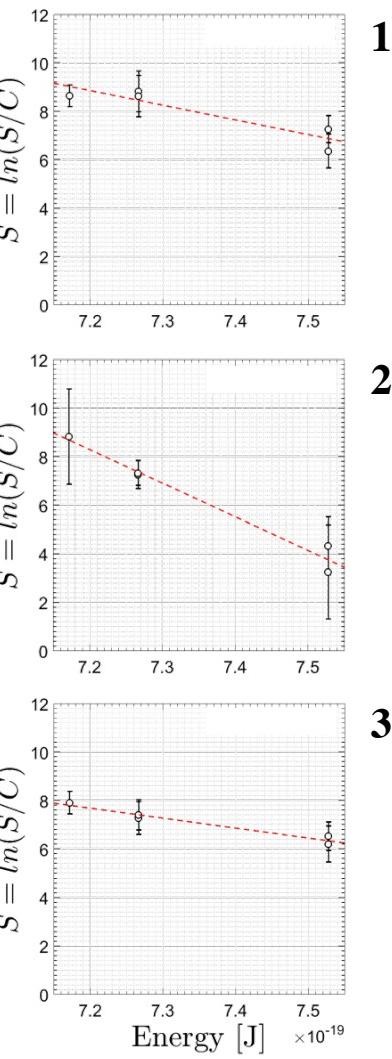
# PLIF Thermometry



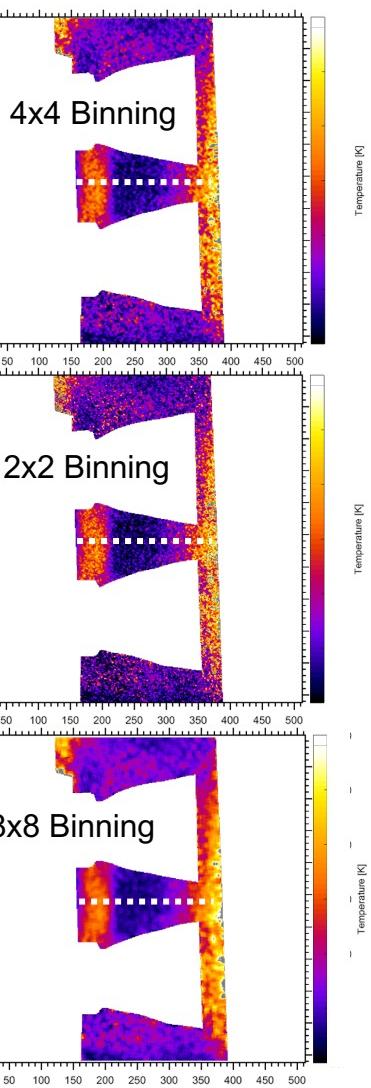
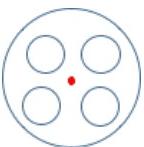
EUS Thermometry – Interrogation – Window  $2 \times 2$

Temperature [K]

## Boltzmann Plots

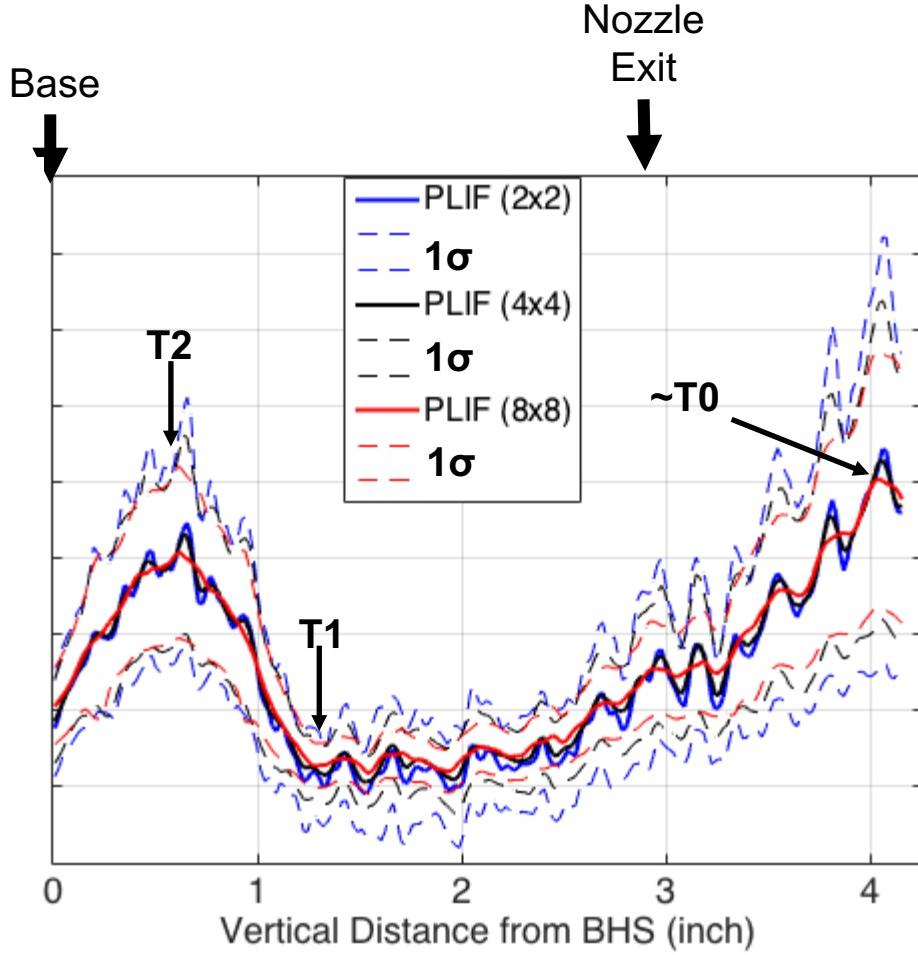


# EUS GT Base Static Temperature Distribution



T1 = Temp Pre Stagnation Shock  
 T2 = Temp Post Stagnation Shock

- Temperature distribution taken along the center of the plume shield to just past the nozzle exit as shown in the dotted white line
- Binning was conducted to obtain mean values and uncertainty statistics of the thermometry PLIF 2D data
- 2x2 binning = uncertainty statistics and mean value were obtained from surrounding 4 pixels
- Dark solid lines are mean distributions and dashed lines are the uncertainty distributions for three binning techniques (2x2, 4x4 and 8x8)





# Conclusions



- TIP & EUS test programs provided for the first time proof-of-concept and technical maturation of non-intrusive diagnostics of visualizing and characterizing complex reacting plume-induced base flows in a ground test facility
- Led to an increase in the technology readiness level (TRL) for short-duration hot-fire test technique and improves confidence in plume-induced flight convective environment predictions
- In the process of developing EUS and SLS base gas temperature maps from PLIF thermometry
  - Historically, experimental base gas temperature data has the highest uncertainty and limited flight data and no temperature map has been obtained to date
  - First time develop a temperature data map of this region to increase the fidelity of base convective heating predictions



# References



- <sup>1</sup>Bender, RL, Lee, YC (1978), IH-39 Base Heating Test Data Analysis, NASA CR NAS8-29270, RemTech Inc., Huntsville, AL
- <sup>2</sup>Mehta, M, (2014), Space Launch System Base Heating Test: Sub-Scale Rocket Engine/Motor Design, Development and Performance Analysis, AIAA 2014-1255, 52<sup>nd</sup> AIAA SCITECH, National Harbor, MD.
- <sup>3</sup>Johansen, CT, McRae, CD, Danehy, PM, Gallo, E., Magnotti, G., Cutler, A., Rockwell, RD, Goyne, CP, McDaniel, JC (2014), OH PLIF Visualization of the UVa Supersonic Combustion Experiment: Configuration A, *Journal of Visualization*
- <sup>4</sup>Danehy, PM, Inman, JA, Alderfer, DW, Buck, GM and Bathel, B (2008), Visualization of Flowfield Modification by RCS Jets on a Capsule Entry Vehicle, AIAA 2008-1231, 46<sup>th</sup> AIAA SCITECH, Reno, NV.
- <sup>5</sup>Brewer, EB and Craven, CE (1969), Experimental Investigation of Base Flow Field at High Altitude for a Four-Engine Clustered Nozzle Configuration, NASA Technical Note, NASA TN D-5165. Led to an increase in the technology readiness level (TRL) for short-duration hot-fire test technique and improves confidence in plume-induced flight convective environment predictions